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Calibration of Geosynchronous Satellite Video Sensors.

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FOR THE COMMANDER

John Howard

Chief Scientist

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This report describes an effort to obtain calibration information for the digital data from the geosynchronous satellite visual sensors. The visual sensor calibration differs for each satellite, and sensitivity may decay over periods of several years. In addition, changes in the NOAA-NESS sensor compatibility table at times affect overall sensor calibration. Tables of calibration factors are presented for GOES-1 and GOES-2, and SMS-1 and SMS-2, for March 1978 through August 1980. Simple, constant calibrations

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20. (continued)

are adequate for less demanding applications such as distinguishing clouds from land or water. Where more precision is necessary, such as identifying haze, one must allow for variations in calibration factors, as presented in the tables.

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1 INTRODUCTION

For over six years the geosynchronous satellites (SMS and GOES) have been routinely transmitting half-hourly images, providing unprecedented views of the structure and behavior of terrestrial cloud patterns. In recent years, scientists[1,2] have been making quantitative use of the visual (0.55-0.75μ) and infrared (10.5-12.6μ) information, to specify and forecast weather parameters such as cloudiness and precipitation. For these studies to produce valid, useful results, there must be long-term stability of sensors, known calibration, and compatibility between satellites. In the case of the IR sensors, there is an on-board absolute calibration system that has proven effective for both the primary sensor and the backup sensor. Calibration of the visual sensors is a more difficult problem. Instead of a single sensor, there are eight parallel visual sensors that sweep a band from west to east as the satellite rotates. The planned on-board calibration system, using reduced direct sunlight, has never functioned properly. The purpose of this report is to provide quantitative information on preflight

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1. Wylie, D. (1979) An application of a geostationary satellite rain estimation technique to an extratropical area, J. Appl. Meteor., 18:1640-1648.

2. Muench, H.S., and Keegan, T.J. (1979) Development of Techniques to Specify Cloudiness and Rainfall Rate Using GOES Imagery Data, AFGL-TR-79-0295.

absolute calibration, present results of simple (albeit crude) monitoring routines, and recommend calibration constants for archived data.

2. SATELLITE VISUAL SENSING SYSTEM

The satellite produces an image when the array of eight detectors sweep west to east as the satellite rotates about an axis parallel to the earth's axis.[3] After sweeping past the eastern horizon, a mirror steps to a more southerly pointing angle prior to the next sweep. To see the process in more detail, consider light from a small region on earth (or atmosphere) being scattered outward in the direction of the satellite. At a certain step in the satellite mirror system, and a certain point in the satellite rotation, the light enters the optics, passes through the lenses and optical fibers, and reaches one or more of the eight parallel photomultipliers.[4] The photomultipliers convert the light to an electric signal, and each photomultiplier has an amplifier to raise the signal to the 0 to 5 V range. All of the eight photomultiplier-amplifier sets are connected to a single analog-to-digital (A-D) converter that has an output range of 0-63 (6-bits, binary), which is proportional to the square root* of the input voltage. This converter samples and converts each of the eight sensor voltages sequentially.

Next, the 6-bit binary numbers are transmitted to the earth control station (Wallops Is., VA, for GOES East), during the brief 30 milliseconds while the sensors are scanning the earth. A computer at the control stations uses the 6-bit number to look up an output number in a calibration table, one table for each sensor, and the number (as well as calibration table ID) is sent back up to the satellite and is rebroadcast to ground stations. This rebroadcast is at a slower baud rate, during the relatively long 570 milliseconds of rotation while the sensors are looking at space.

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3. Corbell, R., Callahan, C., and Kotsch, W. (1976) The GOES/SMS user's guide, NOAA-NESS, NASA.

4. Pipken, F. (1975) Synchronous Meteorological Satellite, System Description Document, Vol. I,II NASA TMX 68845, GPO CSC<22B.

*The square-root function was chosen for signal-to-noise considerations. The function has the effect of providing finer resolution at low brightness levels (e.g., .007 reflectivity per count at a 16 count) and coarser resolution at high brightness (e.g., .028 at 56).

3. INITIAL CALIBRATION (PREFLIGHT)

When the imaging package* is constructed, the eight individual sensing systems are carefully matched for sensitivity, and engineered to produce a nominal 5.0 V output for a reflectance† of 1.00. This 1.00 reflectance would represent light reaching the satellite in orbit, from a perfect diffuse reflector on earth, and with overhead sun that was at an average distance from the earth, with no atmospheric attenuation. The square-root A-D converter is designed to convert a 5.00 V signal to the binary equivalent of 62. Thus, the designed conversion of count to reflectance is given by

$$r = (C/C_o)^2 \tag{1}$$

where C is the output number or count, and C_o is 62.

Actually, performance differs slightly from the design and, to document the performance, a relation between output count and input voltage was determined for a typical A-D converter, and values at 4-count intervals are shown in Table 1.‡ In addition, for each satellite, the output of the eight sensors combined was measured when exposed to a calibrated light source, and values for the same voltages determined from a linear reflectance-to-voltage relation. The Table provides calibrated values of reflectance, voltage, and count for each satellite. The Table also allows one to compute separate C_o's for each satellite, as shown in Table 2.

The specification of reflectivity by Equation 1 is quite precise for count values of 16 and greater,§ but there are small systematic biases at the lower values. A slightly better relation for the voltage to count is

$$V = (C/27.2)^2 + 0.010 \tag{2}$$

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*Commonly called VISSR or Visible-Infrared-Spin-Scan-Radiometers.

†"Reflectance" is a more appropriate term than "albedo" when speaking of sensors, with only 0.55 to 0.75μ bandwidth looking at the earth.

‡Preflight calibration information was supplied to us by Messrs. Lienisch and Ludwig of NOAA/NESS, to whom we are most grateful.

§Value above 16 would result from looking at wooded land with sun above 30° solar elevation, or a light cloud overcast with sun above 5° of elevation.

Table 1. Preflight Calibration of Reflectance ($\times 10^{-2}$) Versus Output Voltage and 6-bit Count

Count	Volts	Reflectance				
		SMS-1	SMS-2	GOES-1	GOES-2	GOES-3
0	0	0.00	0.00	.00	-1.3	-1.1
4	.042	0.85	0.85	0.91	-0.5	-0.2
8	.083	1.68	1.69	1.80	0.3	0.7
12	.208	4.22	4.23	4.51	2.7	3.5
16	.333	6.75	6.77	7.23	5.1	6.3
20	.541	11.0	11.0	11.7	9.2	11.0
24	.749	15.2	15.2	16.3	13.2	15.7
28	1.04	21.1	21.1	22.6	18.8	22.6
32	1.33	27.0	27.0	28.9	24.4	28.7
36	1.71	34.7	34.8	37.1	31.8	37.3
40	2.08	42.2	42.3	45.1	39.0	45.6
44	2.54	51.5	51.6	55.1	47.9	55.9
48	3.00	60.8	61.0	65.1	56.8	66.2
52	3.54	71.7	72.0	76.8	67.2	78.4
56	4.08	82.7	82.9	88.6	77.7	90.5
60	4.69	95.1	95.3	102.0	89.5	104.2
63	5.15	104.0	105.0	112.0	98.7	114.5

Table 2. Calibration Constant C_o Based on Preflight Values (for use with Equation 1)

Satellite	GOES East Period (Julian Days)	C_o (6-bit)
SMS-1	027/1979 through 109/1979	61.5
SMS-2	110/1979 through >270/1980	61.3
GOES-1	<60/1977 through 222/1977	59.4
GOES-2	223/1977 through 026/1979	64.2
GOES-3	not used as GOES East	60.5
GOES-4	expected late 1980	≈62

The first five satellites listed in Table 2 have the following responses based on the ground calibration:

SMS-1	$r = V/4.93$
SMS-2	$r = V/4.92$
GOES-1	$r = V/4.607$
GOES-2	$r = (V - 0.067)/5.162$
GOES-3	$r = (V - 0.049)/4.454$

The small negative voltage constants of -0.067 and -0.049 shown for GOES-2 and GOES-3 represent "dark" currents--a residual voltage output from the amplifiers when no light is impinging upon the sensors. The first three satellites likely had "dark" currents, but the values were not represented in the data provided for Table 1 and, at this point, must be presumed to be negligible.

If Equation 2 is substituted into the five individual r-vs-v response relations, previously shown, we have equations of the form

$$r = a + (C / d)^2 \qquad (3)$$

The resulting values for a and d are shown in Table 3.

Table 3. Calibration Constants a and d, for 8-Sensor Mean (for use with Equation 3)

Satellite	a	d
SMS-1	0.002	61.5
SMS-2	0.002	61.4
GOES-1	0.002	59.5
GOES-2	-0.011	62.9
GOES-3	-0.009	58.5

The constants in Table 2 actually only apply to an average output of all eight sensors. The satellite data in the AFGL/LYU archive[2] consist of "1-mile" data (sum of two adjacent 1/2-mile counts) for every other row; that is, sensors 2, 4, 6, and 8. The average of these four sensors for the calibrated light would likely be slightly different than the average of all eight sensors. The calibration tables used at the ground stations are, in fact, designed to remove incompatibility between sensors, and prevent "striping" in the facsimile pictures. Copies of these tables for GOES East, September 1978-August 1980 were obtained from NOAA,† and by correlating the 8-sensor and 4-sensor average outputs, adjustment factors were found that would allow one to simulate an 8-sensor average, given a 4-sensor average. These factors were used to modify data in Table 3 to produce Table 4.

Table 4. Calibration Constants a and d for 4-Sensor Mean (for use with Equation 3)

Satellite	a	d
SMS-1	0.002	61.6
SMS-2	-0.003	59.4
GOES-1	0.002*	59.5*
GOES-2	-0.012	62.3

*Tables not available; no change from Table 3 assumed.

There is provision in the on-board electronics to modify the sensitivity of any of the eight amplifiers to any of four possible levels, using a command from the ground station. These sensitivity level steps are fairly coarse, and such action would be required only in the case of a gross malfunction. During the past three years, no evidence has been seen that such action has been taken, resulting in the recovery of otherwise useless data. In general, when a sensor has gone bad, all recovery attempts fail, and the ground station substitutes data from an adjacent sensor (or channel), changing the calibration tables to make them match. A code in the documentation part of the transmission indicates sensor substitutions, and another code identifies the calibration table identification.

†September 1978 through August 1980 may be purchased from NOAA Environmental Data Service, Satellite Division, Washington, DC, 20233.

4. CALIBRATION CHECKS USING ARCHIVED DATA

Considering the potential trauma that a satellite could undergo during launch, one must be concerned whether the preflight calibrations still apply after the satellite becomes operational. Further, one must worry whether the transmission of the optics, the response of the photomultipliers, or the amplifier gains might change systematically with time, in the harsh environment of space, where cosmic rays, X-rays, and UV light are far more intense than on earth.

Two, admittedly coarse, calibration procedures were devised. The first consists of monitoring the contrast between the reflectivities of Block Island, RI and the adjacent water. The contrast was chosen, rather than just the island reflectivity, as contrast contains less of the variable contribution of atmospheric scattering. The island was chosen, as it ensures proper navigation. Using Equation 3, and correcting for solar geometry, the contrast can be computed by

$$r_1 - r_w = \left[\frac{(C_1^2 - C_w^2) \ \mathrm{Sec}\zeta}{d^2} \qquad \left(\frac{R_o}{R}\right) \right]^{1/2} \qquad (4)$$

where C_1 and C_w are counts over land and water, ζ is the solar zenith angle, R is the actual distance to the sun, and R_o the average distanc : r_1 and r_w are reflectivities of land and water, and d the satellite constant appearing in Table 4.

The AFGL archive tapes contain data compiled soon after the launch of GOES-2, and these data were used to "calibrate" the land-water contrast in early and late September 1977, hopefully before the preflight calibration had a chance to drift. Hourly calibration values were computed for 1500UT through 1900UT. Even though Equation 4 contains a zenith angle correction, there is a noticeable change in contrast, as the response of the scattering is different for land than for water as the zenith angle changes. Thus, these comparisons can only be made near the equinoxes when solar geometry is similar. The "calibrated" contrast is designated $(r_1 - r_w)^*$ and a new estimate of d is computed from

$$d = \left[\frac{(C_1^2 - C_w^2) \ \mathrm{Sec}\zeta}{(r_1 - r_w)^*} \qquad \left(\frac{R_o}{R}\right)^2 \right]^{1/2} \qquad (5)$$

Another technique that has been suggested[5] for monitoring calibration is to make measurements of scattering from intense tropical cumuliform clouds. An intense storm transmits little light to the ground, and absorbs very little light in the 0.55 to 0.75μ band, and so must reflect only slightly less than 100% of the light it receives. Unfortunately, the AFGL/LYU archive only extends from 47N to 35N, but intense convection does occur somewhere in the area on many of the days during the period from April to August. Designating the brightest count as C_x, we can solve Equation 3, for d

$$d = \frac{C_x}{(r_x - a)^{1/2}} \quad . \tag{6}$$

In order to avoid complications of solar geometry and changing anisotropic scattering, only 1700UT data from May and June were used to find C_x. A value of 1.00 was chosen for r_x, assuming that light from the brightest clouds was enhanced by anisotropic scattering, cancelling loss by transmission absorption. Using histograms, the count level of the 100th brightest measurement in a field of 380,000 measurements from a single image was used for C_x, and the highest C_x of about 15 summer days was used to estimate d.

Resulting estimates for d are shown in Figures 1a and 1b, for the satellites SMS-1, GOES-1, and GOES-2. In general, the calibration estimates indicate no drift of GOES-1 and GOES-2 from preflight values during the period of February 1977 through June 1978. After June 1978 there appears to be a problem with GOES-2. The calibration of both SMS-1 and SMS-2 does not agree with preflight values. The first reaction was to question these coarse techniques, but further inspection of data indicated that, indeed, land and water values were lower in the fall of 1978 than 1977, and counts for brightest clouds were also down. Similarly, reflectivities computed for 1979 and 1980 from the SMS-1 and SMS-2 satellites were consistently lower than those computed from GOES-1 and GOES-2.

5. EFFECTS OF NOAA/NESS CALIBRATION TABLES

As mentioned previously, the NESS calibration tables are used to remove incompatibility between sensors that occurs from time to time due to such factors

5. Vonder Harr, Dr. T. (1979) Personal communication.

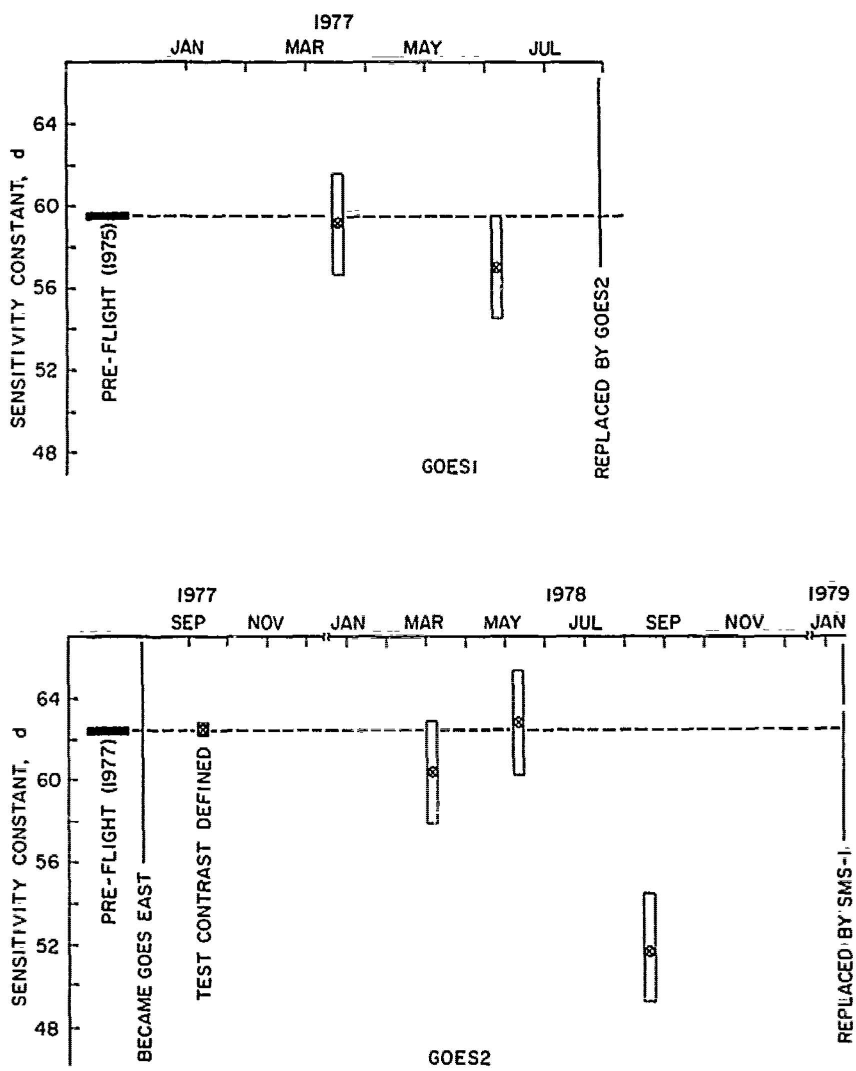

Figure 1a. Calibration Determinations for GOES-1 and GOES-2, Feb 1977-Jan 1979

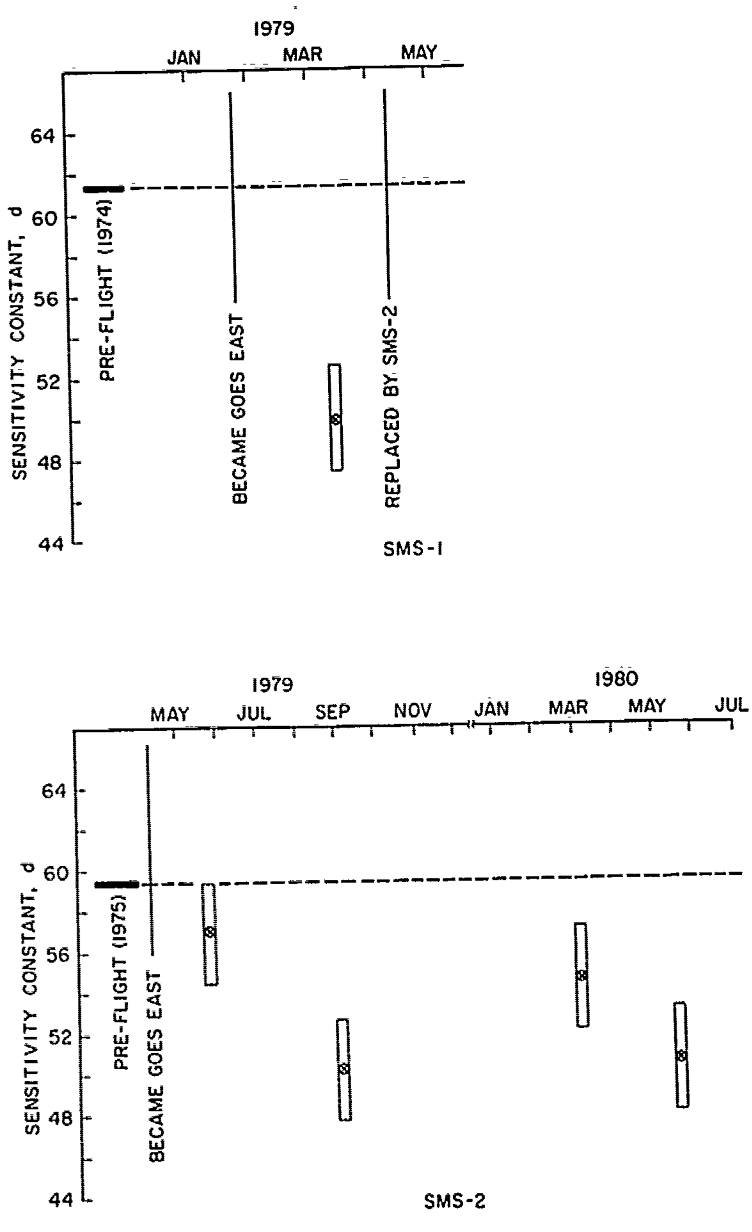

Figure 1b. Calibration Determinations for SMS-1 and SMS-2, Jan 1979-Aug 1980

as different response of amplifiers to small spacecraft temperature changes. When a change in calibration table becomes necessary, to reduce "striping" in images, there is no way to know which sensors are right and which are wrong, since there is no absolute calibration device available. The engineers generally select a "reference" sensor that minimizes the changes. It appears there is a bias towards tables with output numbers that are lower than input, which avoids situations where an input value of 63 would call for an output greater than 63 -- which is not possible with 6 bits. Since there was no absolute guidance, there was a possibility that the changes in the tables could produce the appearance of an instrument calibration drift, particularly for our collection of only four of the eight sensors. A closer study of the calibration tables obtained from NOAA/NESS was made, revealing that, by and large, changes were made about six times a year and were too small to significantly effect the average output of the four sensors. There were several exceptions, as described below.

First, in June 1978, sensor 1 failed, and data from sensor 2 was used in its place. Unfortunately, sensor 1 was the "reference" to which other sensors were adjusted. What followed is illustrated in Figure 2. In the upper portion, the line represents the average output for an input of 60, along with maximum counts -Cx- from 1700UT images of the archive file (as described in Section 4). No change was made in the calibration table until mid-August, and then a series of changes led to successively lower output values. The maximum counts followed the pattern very closely, although, as might be expected, some days did not have very bright clouds. The broken line in the lower portion of the diagram depicts the output for an input count of 14, together with points representing the 100th darkest value, normally the darkest water. Again, there was a marked decrease in the average of the outputs, and the water did become somewhat darker. Obviously, the changes in the calibration tables during August and September of 1978 did make it appear that the sensors had lost sensitivity. In retrospect, most likely sensor 8 was chosen as a new "reference" and, after several months of relative stability, it slowly decreased in sensitivity, while all others were adjusted to it and, in late October or early November, it recovered sensitivity.

In the late spring of 1979, there was a brief, but marked, increase in the average output, quite noticeable for the 60-count level, as seen in Figure 3. Again, this change corresponded to changes observed in the maximum counts. During the few days with high output, the histograms showed serious incompatibility between sensors, as can be seen in the top of Figure 4, and the calibration tables were quickly replaced. These episodes illustrate that not only does one need separate calibration for each satellite, but one needs separate calibrations for

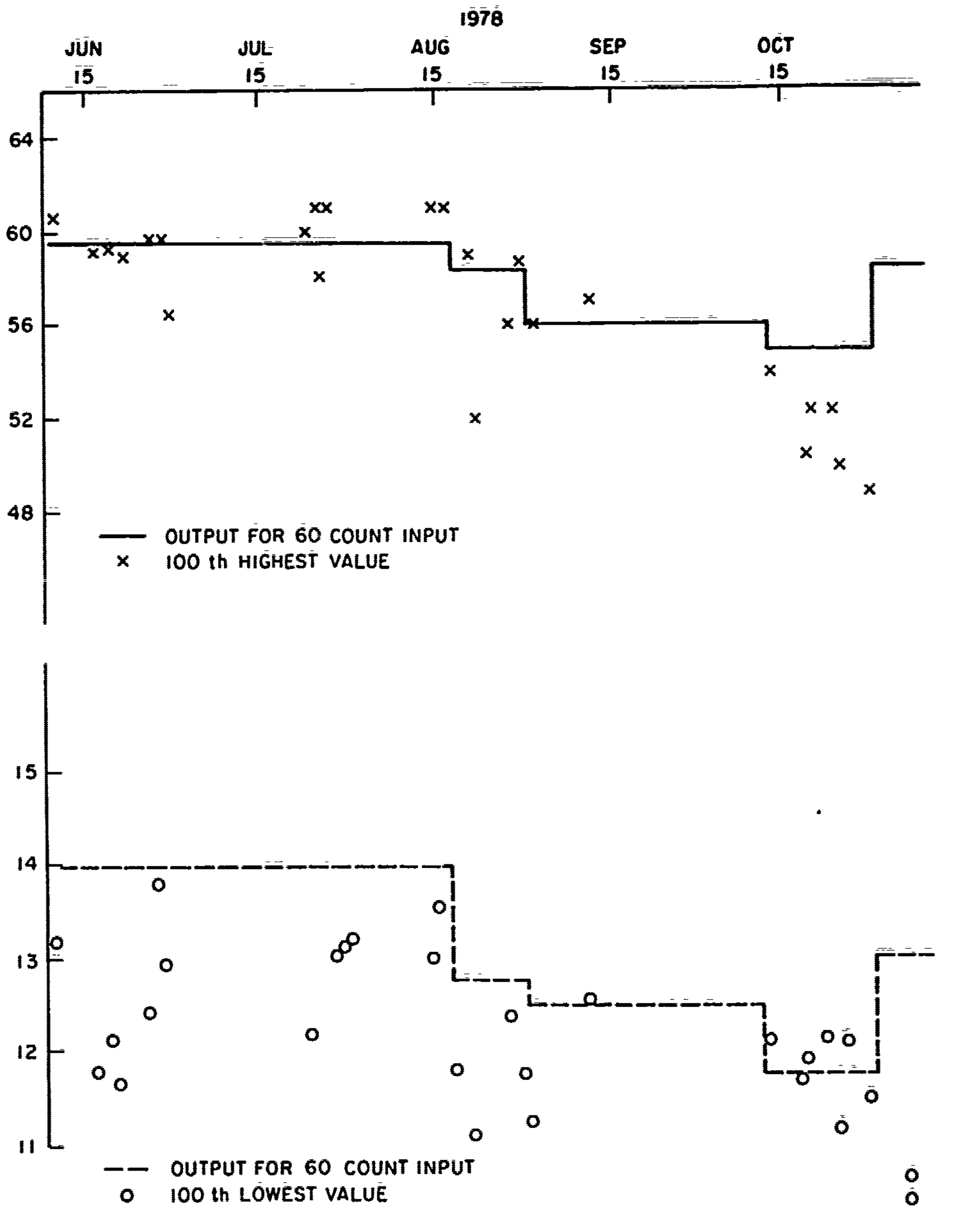

Figure 2. Systematic Changes on 4-Sensor Mean Output due to Changes in NESS Tables, and Changes in Brightest and Darkest Values in Visible Images, June-Oct 1978

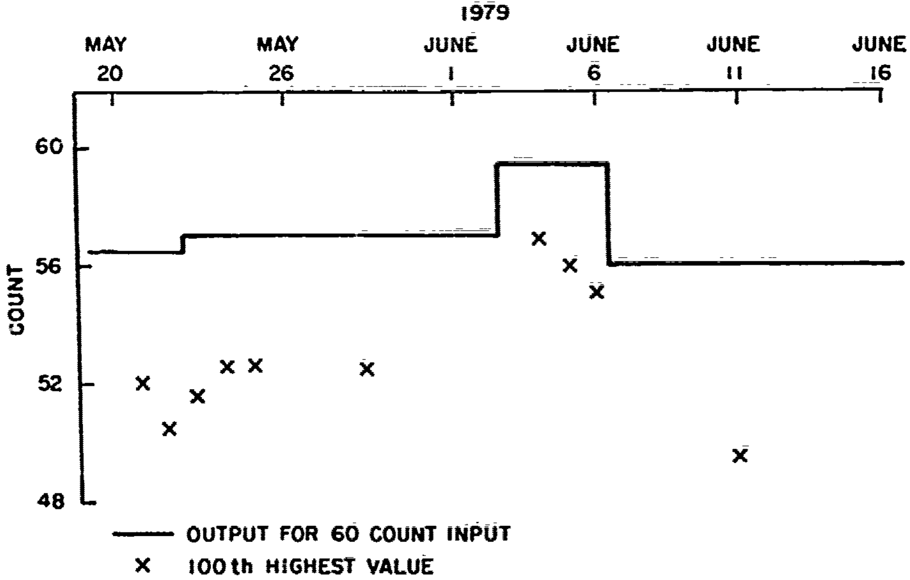

Figure 3. Systematic Changes on 4-Sensor Mean Output due to Changes in NESS Tables, and Changes in Brightest and Darkest Values in Visible Images, May-June 1979

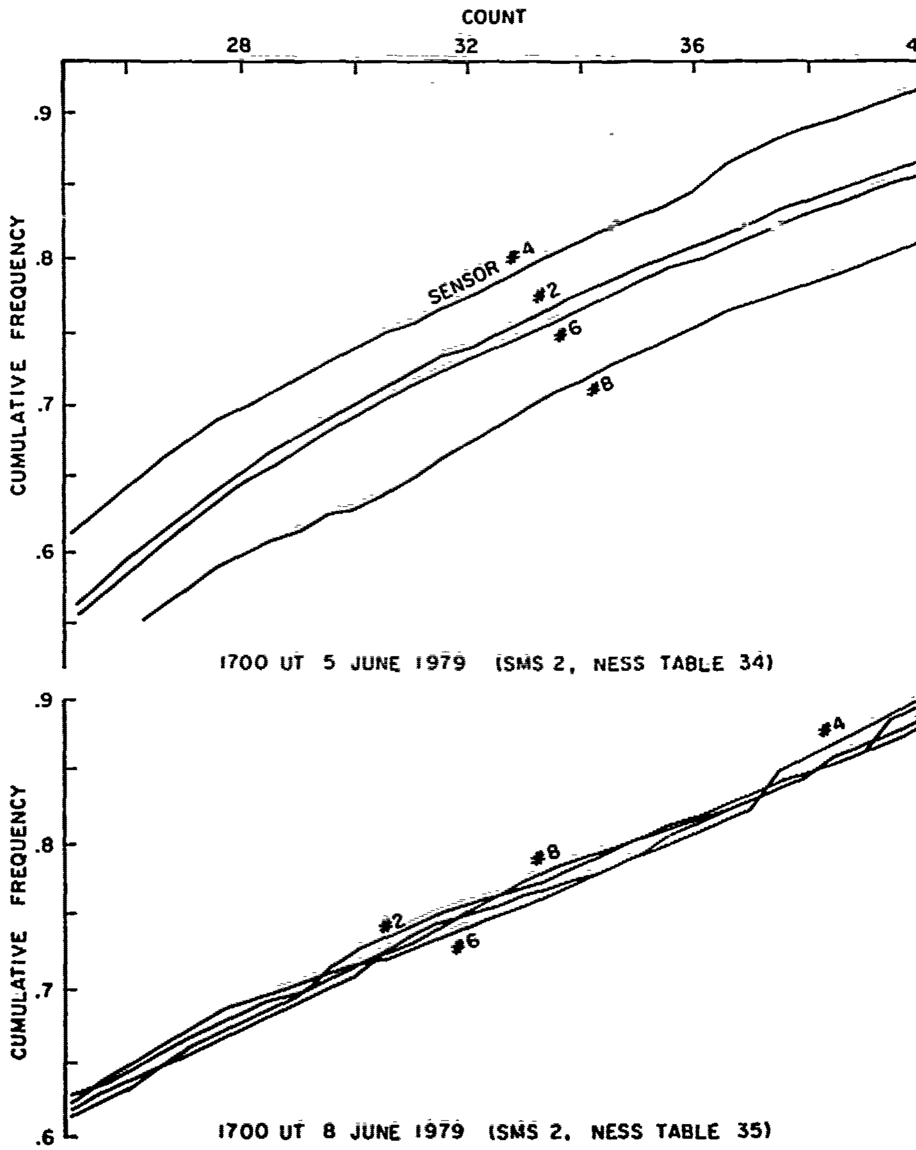

Figure 4. Cumulative Frequencies for Sensors 2, 4, 6, and 8 at 1700UT on 5 and 8 June 1979 (NESS Tables 34 and 35 Respectively)

each NESS calibration table, at least when major changes are made. At NESS, the calibration corrections are made in the form

$$C_n' = C_n - \alpha_n - \beta_n C_n - \gamma_n C_n^2 - \delta C_n^3 \tag{7}$$

where C_n' is the output count for sensor n and C_n the input, while α_n, β_n, γ_n, and δ_n are coefficients chosen to minimize incompatibility. If a nonrepresentative sensor is used as a "reference," then $C_n' - C_n$ will be significantly different from zero when summed over all n sensors. With a little ingenuity, one could use the correction tables to recover the values of α, β, γ, and δ, and invert Equation 7 to solve for a sensor-averaged C as a function of C'. There is some question, however, as to whether such an effort can be justified. Corrections to individual sensors in the form of Equation 7 are quite necessary, and their periodic changes make obvious improvements in the comparisons of histograms. For example, compare the cumulative frequencies shown at the bottom of Figure 4 with those at the top. The necessity for corrections as complex as Equation 7 means that the sensors draft independently in their sensitivity, and not uniformly over their full range. It would seem quite unlikely that even the mean of all eight sensors had a completely linear response (reflectivity-vs-voltage) when the preflight calibration was made. Without knowing the initial nonlinearities, one could easily increase errors by making adjustments for the high order terms in Equation 7. The decision was made, therefore, to include only the two low order terms, and the procedure was simplified to making a linear correlation between C and C', and substituting into Equation 3. The resulting calibration equations are in the form

$$r = a + (C' + b)^2/d'^2 \quad . \tag{8}$$

Once the cause of the apparent loss of sensitivity for GOES-2 in late summer of 1978 had been found, it was reasonable to assume that the values for d shown in Table 3 were valid, and the individual NESS calibration tables resulted in slightly different sensitivities d'. There was no doubt, however, that the sensors on SMS-1 and SMS-2 in 1979 and 1980 were less sensitive that those on GOES-1 and GOES-2. Since SMS-1 and SMS-2 were launched in 1974 and 1975, respectively, such an "aging" might well be expected. While the 1979 tour of SMS-1 as GOES East was short, the archived data suggested a sensitivity d of 55 would be appropriate at that time. For SMS-2, a value of 57 was selected for spring 1979, dropping to 56 for spring 1980.

Amongst the three-thousand-odd images archived were a few that inadvertently began at the top of the full disc picture instead of the programmed start at 47° north latitude. These otherwise unusable images contain data from sensors pointing at space, and can be used to determine the "dark current." The procedure involves taking the measurements and working back through the correction tables and, eventually, an appropriate value of "a" can be computed. Unfortunately, "dark" images from only SMS-1 and SMS-2 were found in the archive.

The resulting value of "a," "b," and "d" are shown in Table 5 for GOES-1 and GOES-2, and in Table 6 for SMS-1 and SMS-2.

6. SUMMARY

As with any weather instrument, effective usage of geosynchronous satellite information requires knowledge of sensor calibration. The absolute calibration of the infrared sensor(s) is maintained using an on-board system. While adjustments of the visual output are made to minimize sensitivity differences among the eight visual sensors, there is no on-board procedure to monitor their absolute calibration.

An effort was made to establish calibration constants for the satellites GOES-1, GOES-2, SMS-1, and SMS-2 operating from 1 March 1977 through 30 September 1980. Reflectance is computed by $r = (C/C_o)^2$, and while design calls for a value of 62 for C_o, preflight calibrations indicate slightly different values for each satellite. Further complications noted were:

1) There is usually a small "dark current" from the sensors, so C does not go to zero when r is zero.

2) The NESS calibration adjustments can artificially alter the calibration constant C_o.

3) Over periods of several years, overall sensitivity can decay noticeably.

Calibration constants were developed which account for these complications. In developing those constants, however, the following assumptions were made:

1) The preflight GOES-2 calibration was still intact one month after being placed in orbit.

2) The linear calibration (voltage output) averaged for sensors 2, 4, 6, and 8 did not change when NESS made sensor compatibility adjustments.

3) Over the eastern United States the maximum reflectance approaches a limit, with similar frequency of occurrence each spring and summer.

A more rigorous calibration procedure is certainly to be desired. The procedure used in developing Table 5 can only be defended as the best that could be done under the prevailing circumstances.

Table 5. Calibration Constants a, b, and d', for 4-Sensor Mean, GOES-1 and GOES-2 (for use with Equation 8)

	GOES-1			
Table	Period	a	b	d'
	<060/1977-222/1977	+.002	0.0	59.5
	GOES-2			
	Period	a	b	d'
01	259/1977-270/1977	-0.011	+0.8	61.8
02	271/1977-300/1977	-0.011	+0.3	59.5
04	301/1977-010/1978	-0.011	+0.2	62.6
05	010/1978-052/1978	-0.011	+0.4	62.3
70	052/1978-111/1978	-0.011	-0.1	59.2
71	100/1978-111/1978	-0.011	+0.0	59.7
72	112/1978-157/1978	-0.011	-0.1	61.9
73	146/1978-157/1978	-0.011	-0.1	62.3
74	157/1978-231/1978	-0.011	-0.1	62.0
77	232/1978-243/1978	-0.011	+1.2	62.2
78	244/1978-250/1978	-0.011	+1.5	60.4
79	250/1978-285/1978	-0.011	+1.4	60.1
65	285/1978-304/1978	-0.011	+1.6	51.6
66	305/1978-362/1978	-0.011	+1.4	62.5
67	363/1978-026/1979	-0.011	+1.4	61.6

Table 6. Calibration Constants a, b, and d' for 4-Sensor Mean, SMS-1 and SMS-2 (for use with Equation 8)

Table	Period	a	b	d'
SMS-1				
Table	Period	a	b	d'
25	027/1979-095/1979	-0.005	0.4	55.5
26	096/1979-109/1979	-0.005	0.4	55.5
SMS-2				
Table	Period	a	b	d'
44	110/1979-124/1979	-0.007	+1.6	55.7
45	125/1979-137/1979	-0.007	+0.5	54.3
46	138/1979-142/1979	-0.007	+0.6	54.4
32	143/1979-150/1979	-0.007	+1.5	55.0
33	151/1979-153/1979	-0.007	+0.8	54.1
34	153/1979-157/1979	-0.007	+0.1	56.9
35	158/1979-242/1979	-0.007	+0.9	54.1
36	243/1979-048/1980	-0.007	+1.1	54.1
37	048/1980-7250/1980	-0.007	+1.0	54.4

7. IMPLICATIONS OF CORRECTIONS

At this point it is appropriate to consider calibration errors, their impact on data usage, and the relationship to other uncertainties. Table 7 summarizes the accuracies of calibration schemes for four reflectances. Assuming Table 5 values were correct, specification errors were computed at 60-day intervals (1977-1980) for the design calibration (C_o=62) and for the preflight calibrations (Table 4). The absolute calibration in Table 5 is certainly not perfect, and an estimate was made that the matching of satellites is no better than ±4%,* and

*The calibration monitoring clearly identified calibration problems when changes of 10 to 15% in reflectance occurred. A residual error of 1/3 the obvious detection level was assumed.

Table 7. Systematic and Random Errors in Geosynchronous Satellite Visual Measurements for 1977-1980

Typical view	Dense cloud	Light cloud	Mixed woods fields	Ocean
Reflectance	.70	.25	.12	.04
Systematic calibration errors--independent of smoothing				
Design: C_0=62	±17%	±18%	±18%	±18%
Preflight: Table 3	±16%	±17%	±17%	±16%
Variable: Table 5	± 5%	± 5%	± 5%	± 5%
Random errors - 1 mi x 1 mi*/4 mi x 4 mi				
1-bit system noise	±2.9%/±0.7%	±4.9%/±1.2%	±6.9%/±1.7%	±11.5%/±2.9%
Round-off	±0.9%/±0.2%	±1.5%/±0.4%	±1.2%/±0.5%	± 3.4%/±0.9%
Residual incompatibility	±1.5%/±0.4%	±2.4%/±0.6%	±3.4%/±0.9%	± 5.7%/±1.6%
Net random error	±3.4%/±0.8%	±5.7%/±1.4%	±8.0%/±2.0%	±13.3%/±3.4%

*In the AFGL McIDAS system, 1 mi x 1 mi values are the averages of two successive 1/2 mi x 1/2 mi counts, for either sensor 2, 4, 6, or 8.

the absolute calibration of GOES-2 was known no better than ±3% for an overall uncertainty of ±5%.

At the bottom of Table 7, a noise level of ±1 count is often quoted for a single sensor observation, which can be readily seen when the sensors are pointing at space or a uniform water surface--elsewhere the noise is lost in natural variability. The round-off to one of 64 values results in a ±.3 count uncertainty. Residual errors such as uncorrected sensor incompatibility, nonlinearities, and NESS calibration round-off amount to be about ±.5 count errors for single observations.

At first glance, the errors arising from use of either the design calibration or preflight calibration appear quite large. Consider, however, that the foliated land is three times as bright as the ocean, and a light overcast cloud condition has twice the brightness of foliage. For many purposes (e.g., navigation, locating clouds) errors of 16 to 18% would not be serious. It is only when one is trying to distinguish haze from clear air, or identify thin clouds, or delineate very dense clouds (heavy rain), that such errors would be important, and for such purposes one would be advised to use Tables 5 and 6.

The random errors are for the most part much smaller than the calibration uncertainty, particularly for the 4 x 4 mile averaged data. In atmospheric visibility studies, the contrast resolution of the human eye is about 2 to 5%, so the satellite is capable of detecting more subtle shading than the human eye, at least for the 4 x 4 averaged data.

In actual use, the limiting factor for accuracy is the absolute calibration. For research purposes, one would like to have calibration errors lower than the estimated ±5% for Tables 5 and 6 in order to determine how much information can be extracted from the satellite data stream. A rigorous calibration program, however, is a tall order. It requires an accurately calibrated sensor with the same spectral response, at a high altitude, looking at the same area at the same time and viewing angle as the geosynchronous satellite. The experiment would have to be repeated for each geosynchronous satellite, at least twice a year. Finally, adjustments would have to be made for characteristics of the NESS calibration tables. Any compromise in these requirements would introduce uncertainties. For example, if the viewing angles differ there are questions of variations in anisotropic scattering; if spectral responses are not identical, questions of reflectance varying with wavelengths; if time is not identical, questions of cloud changes with time. Thus far, no group has felt justified to undertake a rigorous calibration program, although a couple of individual efforts[6] have been made which satisfied most of the requirements. Hopefully, new satellites will present new calibration opportunities in the future that will be seized by researchers.

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